Yih-huei Wan
e-mail: yih-huei_wan@nrel.gov
Phone: (303) 384-7025

Michael Milligan
e-mail: michael_milligan@nrel.gov
Phone: (303) 384-6927

Brian Parsons
e-mail: brian_parsons@nrel.gov
Phone: (303) 384-6958

National Renewable Energy Laboratory,
1617 Cole Boulevard,
Golden, CO 80401, USA

Output Power Correlation Between Adjacent Wind Power Plants*

The National Renewable Energy Laboratory (NREL) started a project in 2000 to record long-term, high-frequency (1-Hz) wind power data from large commercial wind power plants in the Midwestern United States. Outputs from about 330 MW of installed wind generating capacity from wind power plants in Lake Benton, MN, and Storm Lake, Iowa, are being recorded. Analysis of the collected data shows that although very short-term wind power fluctuations are stochastic, the persistent nature of wind and the large number of turbines in a wind power plant tend to limit the magnitude of fluctuations and rate of change in wind power production. Analyses of power data confirms that spatial separation of turbines greatly reduces variations in their combined wind power output when compared to the output of a single wind power plant. Data show that high-frequency variations of wind power from two wind power plants 200 km apart are independent of each other, but low-frequency power changes can be highly correlated. This fact suggests that time-synchronized power data and meteorological data can aid in the development of statistical models for wind power forecasting. [DOI: 10.1115/1.1626127]

Introduction

NREL and its subcontractor Electrotek Concepts are collecting 1-Hz wind power data from two large commercial wind power plants in the Midwest. One is near Lake Benton in Minnesota and the other is at Storm Lake in Iowa (Fig. 1). The Lake Benton wind power plant consists of 138 Zond Z50 variable-speed wind turbines, each rated at 750 kW. The Storm Lake wind power plant consists of 151 Zond Z50 wind turbines. These two wind power plants are in different utility control areas that are interconnected with transmission lines. A more detailed description of these two wind power plants and their locations can be found in references [1] and [2]. Characteristics and simple statistics of the collected wind power data are reported in [3]. This paper describes the correlation between the outputs of these two large wind power plants.

In this region, strong winds are generally associated with the movements of low-pressure systems that originate from the leeside of the Rocky Mountains to the west and cold arctic air from Canada to the north. The wind direction is mainly out of the north to northwest in all seasons except summer [4]. The Lake Benton and Storm Lake wind power plants are about 200 km apart. The terrain between them is generally flat with little surface roughness. In addition, both wind power plants have similar layouts and the same make of wind turbines. Therefore, power output from Lake Benton and Storm Lake over longer time frames, such as hours and days, can be highly correlated, especially in the winter. This knowledge can aid wind power plant and utility grid operators in forecasting wind power.

The power level changes of both plants are confined in a narrow range. In addition, the short-term power fluctuations of these two plants are virtually independent of each other. In sub-hourly and shorter time frames, the wind power outputs from Lake Benton and Storm Lake behave like independent random variables, and the combined output sees a reduction in power level changes. This results in a decreased amplitude in the high-frequency component in the frequency domain.

Inter-Site Correlation and Power System Integration

The correlation of power output between wind power plants can be important to power system operations. A negative correlation occurs if a power increase at one site is countered by a power decrease at a second site. This implies that the net power output of the combined wind sites that have negative correlation has a lower variability than either site on its own. Because wind power plants are part of a larger power supply, this smoothing can help system operators control the conventional power plants to meet the remaining load. There may also be important implications for the costs associated with load following that occur in time frames ranging from a few minutes to a few hours.

In other cases, there may be a positive correlation between wind sites. This often occurs with a time lag that is dependent on the distance between sites and the direction and speed of weather frontal passages. If the time lag is consistent, it may be possible to use the wind power output at one site to predict the future output at another. Prediction of wind power output helps system operators make decisions about which conventional generators to have available to meet the load up to several hours before they are needed.

Finally, two wind power plants at different sites that are uncorrelated are statistically independent of each other. Probabilistically, this implies that increases at one site may be accompanied by increases, decreases, or no changes at another site. Statistical independence is a powerful force in power system operations. This independence also applies to customer loads—not all customers will reach their peak demand simultaneously. Therefore, wide variations in individual customers tend to smooth out with aggregation. In the context of wind power plants, this implies that independent levels of outputs from different plants also tend to smooth out over large numbers of wind turbines that are spread over long distances. These implications are explored further with collected data in later sections of this paper.

Low-Frequency Correlations

A comparison of the output power from both wind power plants for longer time frames, such as several hours or several days, shows a strong correlation between the two. Figure 2 shows daily outputs of Lake Benton II and Storm Lake for a three-month period. Outputs from these two locations track each other very

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closely on a day-to-day basis. The correlation coefficient during this period was 0.744, confirming the visual observation. On a monthly basis, the correlation coefficients of daily outputs are all positive numbers. They range from 0.647 to 0.925. Table 1 lists the monthly correlation coefficients of hourly outputs for 2001 and 2002.

Low-frequency variations in the outputs from Lake Benton II and Storm Lake during longer time frames (hours and days) are highly correlated (i.e., they are not independent; the weather system that drives the wind affects both plants because of their relatively close proximity).

Figure 3 illustrates the low-frequency correlation between Lake Benton and Storm Lake with a plot of 1-minute average power profiles from both wind power plants for a seven-day period (168 h). The similarity between the two profiles in Fig. 3 clearly points out how Storm Lake outputs are related to Lake Benton II outputs during this 7-day period. Daily output correlation coefficient for this period is 0.851. In addition Fig. 3 suggests that a certain temporal relationship exists between the outputs of these two wind power plants. Calculation of cross-correlation coefficients between Lake Benton II and Storm Lake reveals more information about this relationship.

Figure 4 plots the cross-correlation coefficients between Lake Benton and Storm Lake for four data series of different lengths:- 1 day (the first 24-h period in Fig. 3), 2 days (the 48-h period of day 1 and 2), 3 days (the 72-h period from day 1 to day 3), and 4 days (the 96-hour period from day 1 to day 4). The figure shows a time shift of the Storm Lake power signal from −720 min (i.e., advancing the Storm Lake data series 12 hours relative to that of Lake Benton) to +1080 min (delaying the Storm Lake data series 18 h relative to Lake Benton) in one-minute increments.

The one-day data series displays a strong correlation between these two power series when the Storm Lake data are shifted about +272 min (4 h and 32 min). The two-day data series shows a strong correlation at +240 minutes (4 h). This corresponds to the time it would have taken for the weather system to travel from Lake Benton to Storm Lake given the wind speed and direction

Table 1 Correlation of daily outputs

Month	2001	2002
January	0.695	0.647
February	0.681	0.782
March	0.736	0.751
April	0.797	0.842
May	n/a	0.873
June	0.816	0.925
July	0.898	0.752
August	0.808	0.794
September	0.787	0.743
October	0.903	0.840
November	0.836	0.669
December	0.812	
Yearly	**0.809**	**0.818**

Fig. 1 Wind power plant locations

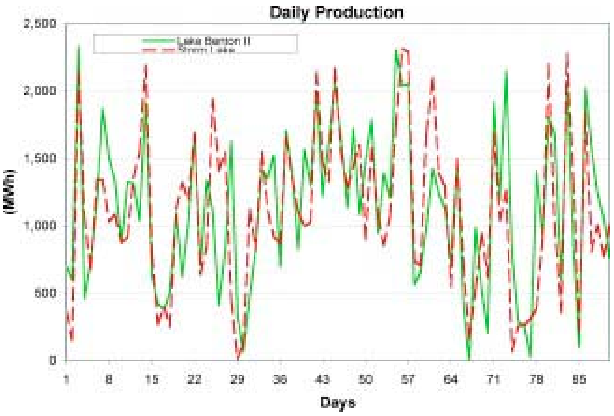

Fig. 2 Daily outputs of Lake Benton II and Storm Lake

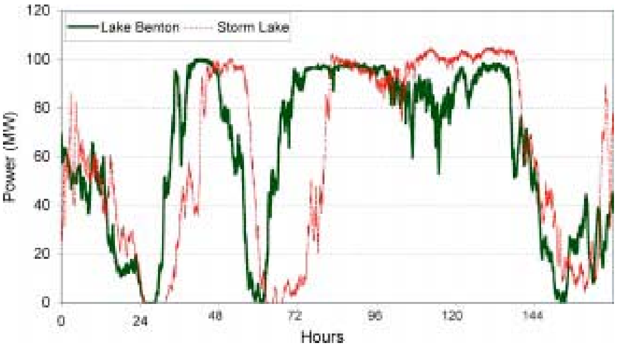

Fig. 3 Weekly output power example

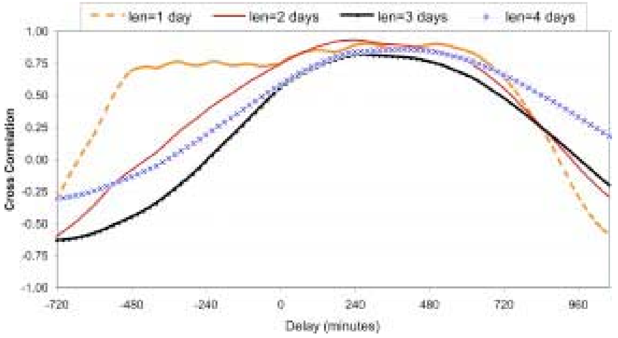

Fig. 4 Cross correlation between Lake Benton II and Storm Lake

recorded at the time. Figure 5 shows the hourly average wind speeds of both locations for the first 96-h period in Fig. 3.

The output power profiles shown in Fig. 3 and the plot of average hourly wind speeds in Fig. 5 show that well-defined weather systems passed through both wind power plants. The weather systems experienced at Lake Benton moved on through Storm Lake after a delay that can be estimated from a cross-correlation plot. Because the same type of turbines are installed at Lake Benton and Storm Lake and the layouts of the wind power plants are similar, the resulting power output from both wind power plants is similar. Meteorologists can predict how fast a weather front travels and when it will reach a certain point. With this knowledge and knowledge of the wind power plant characteristics, the output of the downwind wind power plant can be predicted from the output power of the upwind wind power plant.

The one-hour average output power data of the power profiles shown in Fig. 3 were used to test if such a prediction method is feasible. For the 36-h period that contained the first prominent feature in Fig. 3 hourly output from Lake Benton predicted hourly output of Storm Lake four hours later at an average error of −4.1 MW (less than 4% of the rated capacity). The standard deviation of such a prediction error is quite large at 14.8 MW. Part of the error can be attributed to the size difference between the two wind power plants (Lake Benton is 10 MW smaller than Storm Lake).

Despite this built-in bias caused by the difference in power plant size, the time-shifted prediction method still yields a smaller standard deviation value than a straight-forward persistency prediction method in which previous hourly output is used to predict the output of the next hour (i.e., $P[i+1]=P[i-1]$ at 2-hour persistence). Average error for the persistency model during the same period was 0.4 MW with a standard deviation of 17.8 MW, indicating the presence of larger forecasting errors with the simple persistency model.

This paper does not purport to examine wind power prediction methodology. The above example serves to emphasize the output power correlation between two separate wind power plants in the same wind regime.

High-Frequency Power Fluctuations

When comparing the two outputs for shorter time frames, different correlation patterns appear. Taking the data in Fig. 3 as an example, the correlation coefficient calculated from hourly average power for the 7-day period is 0.693. Although this value still points to a strong positive correlation, it is noticeably smaller than the correlation coefficient value of 0.851 calculated from daily energy for the same period. On a daily basis, the correlation between hourly average power of Lake Benton II and Storm Lake varies from 0.851 to −0.550 (Table 2). Thus, instead of always tracking each in the same direction, the hourly outputs from Lake Benton II and Storm Lake at times persistently move in opposite directions.

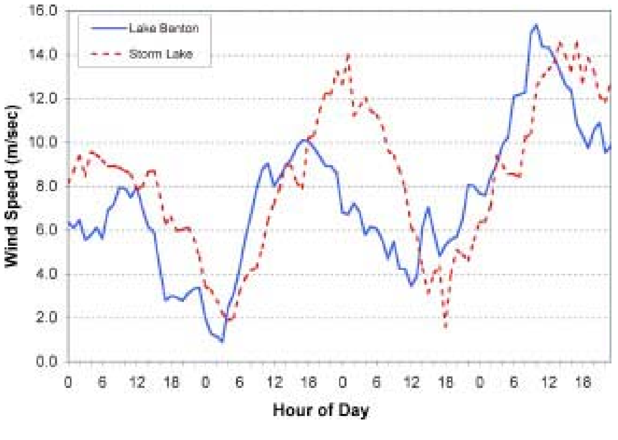

Fig. 5 Average hourly wind speed for a 96-h period

Table 2 Daily correlation coefficients from hourly average power

Day	Correlation Coefficient
1	0.794
2	0.851
3	0.324
4	0.622
5	−0.550
6	0.803
7	0.405
7-day period	**0.693**

Table 3 Monthly correlation coefficients of one-minute data and their daily ranges

2001	Monthly Correlation Coefficient	Range
January	0.530	(−0.528∼0.748)
February	0.568	(−0.297∼0.969)
March	0.606	(−0.106∼0.901)
April	0.630	(−0.320∼0.980)
June	0.645	(−0.416∼0.877)
July	0.687	(−0.298∼0.912)
August	0.539	(−0.462∼0.920)
September	0.644	(−0.487∼0.952)
October	0.757	(−0.413∼0.910)
November	0.661	(−0.132∼0.916)
December	0.732	(−0.173∼0.895)

For shorter time frames, the lack of consistent correlation between Lake Benton II and Storm Lake is even more prominent. With one-minute average power data, the 168 hourly (60 data pairs for each hour) correlation coefficients between Lake Benton II and Storm Lake during the same seven-day period range from −0.942 to +0.987, with an average value of 0.054. Using 1-second power data to calculate correlation coefficients for a period of 10 minutes (i.e., with 600 data pairs for each interval) results in correlation coefficient values ranging from −0.920 to +0.961. The average value is −0.059, which indicates that, in 10-min intervals, the second-by-second power outputs are not related. Carrying the computation procedure of correlation coefficients further into one-minute intervals (i.e., with 60 data pairs for each minute) results in an average correlation coefficient value of only 0.004 (ranging from −0.976 to +0.992). Correlation coefficients calculated from large samples of two random data series should have a mean value of 0. The rapid approach of the calculated value to 0 suggests strongly that the high-frequency components of output power from Lake Benton and Storm Lake are nearly independent. Calculations with 2001 data set (365 days) support this conclusion.

Calculations of daily and monthly correlation coefficients with one-minute average power data points provide further support that, in longer time frames, the power outputs from these two plants are highly correlated despite the stochastic behavior of their short-term power fluctuations. Table 3 lists monthly one-minute power correlation coefficients and the ranges of daily one-minute power correlation coefficients within each month. This shows that on a daily basis, the one-minute average power of these two wind power plants can vary significantly from a highly positive relation to a highly negative relation. However, on a monthly basis, the correlation coefficients are remarkably high and consistent (indicating a high degree of correlation) throughout the year. This result again demonstrates the underlying dependence of longer time frame power variations of the two wind power plants despite the obvious random behavior of short time frame power fluctuations.

Because the higher-frequency variations of wind power from these two sites are nearly independent, the combined power outputs will have fewer high-frequency variations. This can be seen in the Beyer [5] and McNerney [6] studies that investigated the smoothing effect of wind power from multiple wind power plants. Figure 6 shows a power spectrum density plot evaluated from 10,080 one-minute average power data points from Lake Benton, Storm Lake, and the two combined (the same data set was used to plot Fig. 3). The power data series were normalized by dividing each data point by the average power of the series. The graph shows fewer high-frequency components in the combined power.

The reduction in power level variations with the increased number of wind turbines and wind power plants can also be seen in the computed variances of the wind power step changes in Table 4. To remove wind power plant size bias, the one-minute power series is normalized by dividing each data point by its rated capacity before the step differences and their statistics are calculated. Table 4 only lists the monthly standard deviation values for 2001. As expected, the variances of the step changes of the combined power outputs are less than those of the individual wind power plants. If Lake Benton and Storm Lake were the same size and their outputs were completely independent, the normalized standard deviation of combined power would be 0.707 $(1/\sqrt{2})$ times the individual standard deviation. The values of column three in Table 4, although close to the theoretical value, do not satisfy this relationship because power outputs of Lake Benton and Storm Lake are not totally independent. However, the reduction is clearly present. When compared to the individual wind power plant outputs, the combined output shows a 20% reduction in minute-to-minute power fluctuations at Lake Benton and a 40% reduction at Storm Lake.

The advantages of having multiple wind power plants that reduce power fluctuations because of spatial variations of wind resources are also evident in peak power and minimum power. For example, during the 18-month period from January 2001 to June 2002 there were 54 days when daily peak powers of Lake Benton, Storm Lake, and their combined power all occurred at the same hour. However, on a monthly basis, none of the peak combined power conditions during those 54 days when all three powers peaked concurrently was high enough to be the peak power of the month. Table 5 shows the day and hour of each month when monthly peak power occurred at Lake Benton, Storm Lake, and at their combined power. The last column in Table 5 lists the ratio of coincidental peak power (peak power of the combined output for the month) to non-coincidental peak power (the sum of individual peak powers for the month). The ratios for all the months are less than 1, as expected. During this period, there were only three occasions when the combined power on a monthly basis peaked on the same day (shown in bold in Table 5) as the individual plant peak days. Even on those three days, the output power at the individual wind plants peaked at different hours. The data show that the peak of combined power was always smaller than the sum of peak powers from individual wind power plants.

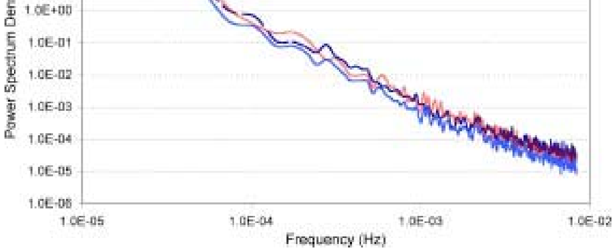

Fig. 6 Power spectrum densities from individual and combined wind power plant outputs

Table 4 Standard deviations of normalized minute step change values

2001	Lake Benton	Storm Lake	Combined
January	0.0057	0.0049	0.0037
February	0.0067	0.0054	0.0043
March	0.0059	0.0087	0.0053
April	0.0088	0.0199	0.0112
May	0.0080	n/a	
June	0.0099	0.0093	0.0067
July	0.0067	0.0055	0.0043
August	0.0064	0.0051	0.0041
September	0.0062	0.0051	0.0040
October	0.0084	0.0070	0.0054
November	0.0066	0.0058	0.0044
December	0.0067	0.0057	0.0053
Average	**0.0073**	**0.0085**	**0.0057**

Table 5 Day and time of monthly peak power

Year and Month	Lake Benton		Storm Lake		Combined		
	Day	*Hour*	*Day*	*Hour*	*Day*	*Hour*	*CP/NCP*
2001							
Jan	**25**	**7:00**	**25**	**18:00**	**25**	**18:00**	**0.90**
Feb	9	3:00	25	0:00	25	8:00	0.97
Mar	**15**	**0:00**	**15**	**9:00**	**15**	**5:00**	**0.99**
Apr	18	5:00	23	16:00	23	15:00	0.99
Jun	23	8:00	12	15:00	13	14:00	0.95
Jul	1	3:00	31	21:00	6	11:00	0.97
Aug	**29**	**14:00**	**29**	**20:00**	**29**	**20:00**	**0.91**
Sep	1	6:00	14	14:00	11	3:00	0.96
Oct	31	5:00	24	23:00	25	16:00	0.99
Nov	8	22:00	9	2:00	9	4:00	0.99
Dec	1	19:00	2	2:00	2	4:00	1.00*
2002							
Jan	22	6:00	26	20:00	3	20:00	0.98
Feb	22	19:00	26	9:00	14	4:00	0.99
Mar	14	15:00	14	1:00	20	19:00	0.98
Apr	6	12:00	2	16:00	9	22:00	0.99
May	4	3:00	9	13:00	9	7:00	0.99
Jun	19	6:00	2	19:00	2	17:00	0.97

*actual value 0.995 rounded up to 1.00.

Analysis of minimum power production provides additional evidence on the smoothing effect of multiple wind power plants. Minimum power for wind power plants is zero power output. On an hourly basis, there were 326 hours during 2001 when the output power was zero at Lake Benton and 535 hours at Storm Lake. For the combined power, however, there are only 162 hs in 2001 when the output power was zero. Regardless of what caused the zero power outputs (forced and planned outages or calm wind), the effects of spatial variations of wind resources and dispersion of wind turbines are clear. Lower maximum and higher minimum of the combined wind power from Lake Benton and Storm Lake effectively reduced the range of combined wind power fluctuations. In addition, the decrease in zero power output hours is equivalent to improved plant availability or reduced plant forced outage rate. Either one of these changes can improve wind power plant capacity credit as computed by traditional utility reliability indices.

A similar smoothing effect from geographically dispersed wind plants has been found in other studies. Milligan and Factor [7] analyzed 12 potential wind sites in Iowa and found that geographic dispersion yielded larger economic and reliability benefits than wind development at a single site. Milligan and Artig [8] showed similar results in an analysis of six potential sites in Minnesota. In both of these studies, geographic dispersion reduced hourly variations in wind power output by approximately two-thirds compared to a single site.

Conclusions

Wind power data collected from Lake Benton and Storm Lake showed that outputs from the two wind power plants exhibit a high degree of correlation because of their proximity. Both wind power plants were often subject to the same weather systems with similar wind conditions, and their power outputs were often of similar magnitude and profile. Over a course of one day or several days, low-frequency variations of power levels were not found to be independent from each other. Outputs at the downwind plant could be predicted with relatively high accuracy based on outputs from the upwind plant, if the relevant meteorological information was available.

Physical separation of wind turbines on multiple wind power plants and the stochastic nature of wind speed over time and distance make it unlikely that any correlation patterns exist for short-term wind power outputs from separate wind power plants. High-frequency wind power level fluctuations are random and independent from different wind power plants. As a result, high-frequency power level fluctuations in the combined outputs of the two wind power plants are reduced or ‘‘smoothed out.’’ Collected data confirm such behavior. The longer the distance between wind turbines, the less likely the combined wind power will show extreme conditions. This effect can decrease the effect of wind power on system regulation requirements as more wind power capacity is installed.

In conclusion, the data show a high correlation of longer-term power outputs between Lake Benton and Storm Lake, whereas high-frequency power variations are statistically independent. These facts facilitate the forecasting of wind power output of large wind plants and lessen the burdens caused by large wind power plants on electric system operations.

Future work will investigate the correlation between wind power plants separated by even greater distances to see how large-scale wind power plants will behave and how they can contribute to the system reliability.

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